Development of a Radar/SAR Assimilation System for Internal Wave Prediction

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LONG-TERM GOALS

Oceanic internal waves, particularly large non-linear ones, can have a significant impact on ship and submarine operations when they move through a region due to the surface currents and buoyancy issues such waves induce. Thus the Navy has a need for a predictive system that can tell a ship or submarine what the future internal wave effects will be in their region.

The long term-goal of this project is to provide a component of such a predictive system that will take remote sensing imagery of a region and estimate the current internal wave characteristics within that region. It is then anticipated that these internal wave characteristics will be handed-off to an internal wave propagation model that will generate the future characteristics of the internal waves.

OBJECTIVES

This program will focus on utilizing synthetic aperture radar (SAR) or real-aperture radar (RAR) imagery to characterize internal waves. A SAR or RAR system will only image surface effects on the ocean (such microwave sensors do not penetrate into ocean any significant depth), so internal wave characteristic will be derived from their surface manifestations. The most significant surface effect will be a modulation of the surface current due to the passage of the internal wave. Thus the program will focus on estimating surface currents from radar cross section imagery (from either SAR or RAR systems) and using those to estimate internal wave characteristics. The program has four objectives.

(1) ***Inversion of radar cross section signatures to surface current gradients and internal wave characteristics.*** This is the development of a tool to take the radar cross section image and generate estimates of surface current gradients

(2) ***Automated internal wave detection.*** This will develop a tool to automatically locate internal wave signatures in radar cross section imagery and estimate their propagation characteristics from multiple imagery.

(3) ***Development of the end-to-end system***. The two components developed above will be put together into a single, automated, system and validated at a sponsor-determine location with *in situ* observations of the internal waves for comparison.

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(4) ***Documentation.*** The final objective will be to provide documentation for the final system and its validation.

APPROACH

(1) Inversion of radar cross section signatures to surface current gradients and internal wave characteristics.

This effort will be to build the inversion scheme to estimate surface currents and model parameters from RCS signatures. We anticipate that this will be an iterative approach, where we start with initial guesses for the current gradients and model parameters, and then successively improve them until the simulated RCS signatures from the forward model matches the observed RCS signature. The key to such a scheme is the estimation of the gradient of the error (where the error is between the simulated and actual RCS observations) with respect to the parameters being estimated (i.e. current gradient field and model parameters). We will investigate a number of ways to generate this error gradient. One will be to assume a functional form for the surface currents induced by the internal wave, then numerically calculate the error gradient via small perturbations of the parameters for the surface current function as well as the forward model. This will be effective as long as the number of parameters is small. We will also investigate removing the need for a functional form of the current, and directly estimate the two-dimensional current gradient field. This will require estimating the error gradient via the inversion of the forward model, since the number of parameters will be too large for numerical techniques. The model inversion will be performed via adjoint techniques, for which the models are run backwards with errors as “inputs” and thus gradients as “outputs” to the adjoint or inverse model.

(2) Automated internal wave detection

Some work in this area has been going on in Europe under the Marine SAR Analyses and Interpretation System (MARSAIS) program using wavelet analysis. Under our existing NOAA/NESDIS programs we have been collaborating with the MARSAIS staff on wind and ship algorithms; we anticipate continuing this collaboration to include internal wave algorithms. We will first determine what the state of the art is in the MARSAIS project, and then use this as a base for our development. The biggest problem for an operational system will be the rejection of false alarms; something that the MARSAIS project has not focused on. We anticipate that this will require spatially locating proposed internal wave packets on a map, and then utilizing their relative relationship with each other (i.e. true internal wave packets will be along some line with some generally known spacing) as well as their relationship to the coastline (i.e. true internal waves will propagate in known areas and directions). This will help eliminate errant signatures from surfactants or wind rows that may locally have similar characteristics to internal wave signatures, but globally are not in the appropriate locations.

The final step in this task will be to take the master list of internal wave packet properties and derive local oceanic environmental conditions. This part of the system will allow the user to specify sets of assumptions (i.e. a two-layer model, constant depth of the upper layer, known bathymetry, etc.) and will then derive the oceanic conditions consistent with the internal wave packet characterizations and these assumptions. We will utilize the same techniques as have been discussed in the literature; thus this step will be dominantly an implementation of known techniques.

(3) Development of the end-to-end system.

The task will combine the two previously developed tools and put them together into a single, automated, tool. This approach will be straightforward connection of the two tools. Then the system will be validated on some sponsor-determined location.

(4) Documentation

Documentation for the tool and the validation process will be generated

WORK COMPLETED

The system to invert radar cross section modulations (Task 1 above) is completed and has been tested on a limited data set (see below). We are in the process of developing the automated internal wave detection codes (Task 2 above) but have completed the estimation of local oceanic conditions from the internal wave properties using a two-layer model (also Task 2). We are finalizing the end-to-end system and documentation (Tasks 3 and 4 above).

RESULTS

The inversion tool for estimating surface currents from radar cross section modulations (RCSM) has been completed and is being tested. Figure 1 shows a flowchart of the tool which consists of two parts. The top section of Figure 1 is a forward model that generates simulated RCSM from an assumed surface current field. The bottom section of Figure 1 is the inverse model that takes as input the error between the simulated RCSM and the actual RCSM extracted from the SAR image, then determines the change in surface current required to decrease this error. The bottom section is done by estimating the gradient of the error with respect to the surface current, then moving the surface current values in the conjugate gradient direction based on the gradients. Thus the whole system is a conjugate gradient search for the surface current field that minimizes the error between the simulated and actual RCSM.

The forward model in Figure 1 first solves the wave action balance equation to determine the spatial changes in surface wave spectra as they propagate across the surface current field. These wave spectra are then put into a radar cross section (RCS) model that generates the normalized RCSM to compare to the SAR imagery. The wave action balance equation (see, for example, Lyzenga and Bennett (1988) for a full description), written in a simplified form for clarity that assumes that the surface currents are only in one direction and only changing in the x-direction, is

$$\frac{\partial A}{\partial t} + \left(u + c_{gx}\right)\frac{\partial A}{\partial t} - \left(k_x \frac{\partial u}{\partial x}\right)\frac{\partial A}{\partial k_x} = F_S \qquad (1)$$

where A is the action defined as the wave spectrum divided by its frequency, the left hand side represents the transport of action in both space and spectral domains, and F_S represents all of the processes that are putting energy into the waves or taking energy out of the waves. To solve Eq. (1) we use a ray trace approach with a fifth-order Runge-Kutta method. The ray trace approach solves for

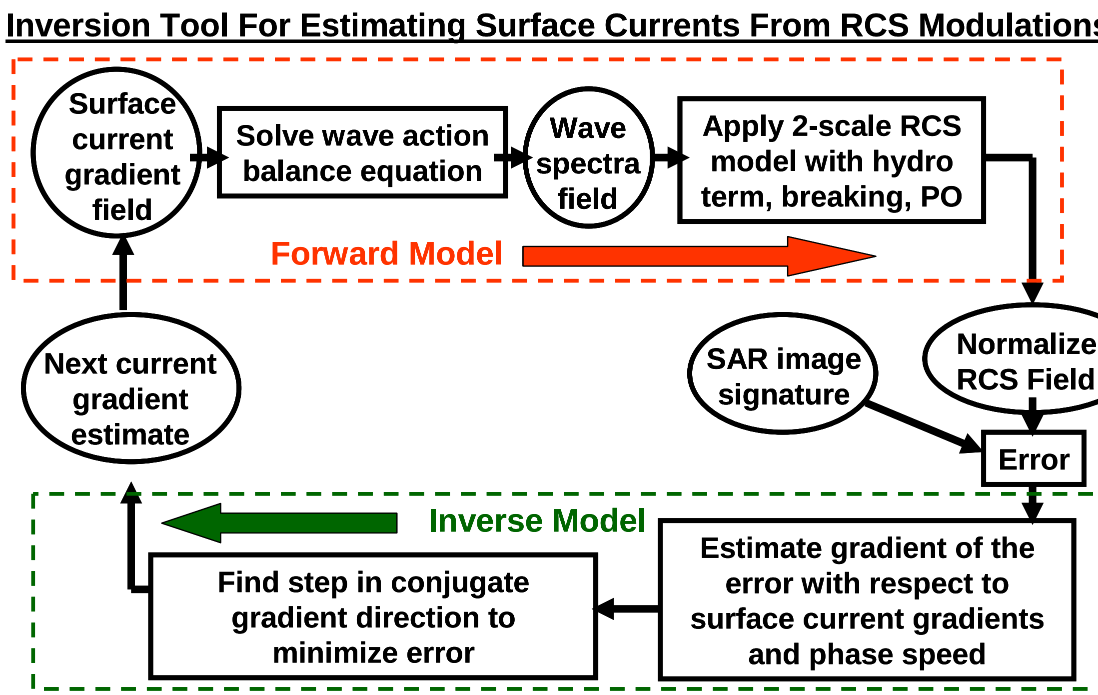

Figure 1: Flowchart for the inversion tool.

the action at a give spatial location and for a given spectral location by first determining where in the spatial domain this spectral component came from and then determining how its action changes as it propagated to its current position. Thus Eq. (1) is first solved backwards in time with the right hand side, F_S, set to zero. This backward solution is stopped when we are well outside of the region of changing currents. At this point we assume that the wave energy is strictly determine by the model for the equilibrium wind wave spectrum. We then set the action using the equilibrium spectrum, then solve Eq. (1) forward in time with the correct sources and sinks of energy in F_S until we get back to the original spatial location (and time value). We now have the action value at the original (x,y) and (k_x, k_y) locations.

We implemented a perturbation model for the right hand side, F_S, of the form

$$F_S(A) = \left(\beta - 4\upsilon k^2\right)A + \left(4\upsilon k^2\right)A_o - \beta \frac{A^n}{A_o^{n-1}} \qquad (2)$$

where A_o is the equilibrium action, β is the wind growth term (that determines how much energy is put into the wave system from the wind), ν is the surface viscosity (which takes energy out of the wave system), and the last term in Eq. (2) lumps together all the non-linear sinks (such as wave breaking) of wave energy. In addition, there is often a spectral energy transport term added on to the expression in Eq. (2) which we have ignored due to the short time over which we are modeling the surface waves. We use a value of n=2 (this gives the largest perturbation values) and the Plant & Wright 1977 term for the wind growth, β.

The final part of the forward model is the generation of the RCSM from the wave spectra. This utilizes a model that had been developed under previous programs which contains three scattering contributions to the RCSM. The first is a tilted Bragg two-scale model that incorporates the tilting of the small-scale Bragg waves by the large-scale waves and the hydrodynamic modulations of the Bragg wave amplitudes by the surface currents induced by the orbital velocities of the large-scale waves. The second is a physical optics term for specular scattering from ocean surfaces that are "glinting" to the radar. See Wackerman et al., (2002) for details on these terms. The third term is for breaking water regions where the fraction of breaking is determined from the distribution of downward acceleration within a ocean surface cell and the RCS for the breaking region is determine from *in situ* observations that have been done on breaking water (Ericson et al., 1999; Haller and Lyzenga, 2003). All of these terms can be generated from the wave spectrum, thus each location where a two-dimensional wave spectrum has been generated via the solution of Eq. (1) we then generate a single values for the RCSM at that location. Doing this at a series of spatial locations we can generate a plot of RCSM values across the surface current field.

For the inverse model, after having experimented with a number of gradient approaches for a continuous current, we have determined that a more robust approach is to assume a sech^2 or (1+cos) form for the current field from an individual internal wave and then iteratively derive the peak/width values for each wave. We set the number and locations of the internal waves using the original RCSM under a small amplitude approximation; then we iterate on the peak/width values of each internal wave current field till we can match the RCSM.

Finally we have implemented an algorithm to estimate the local oceanographic parameters for the SAR-derived information using a two-layer internal wave model (Choi and Camassa, 1999; Zheng et al., 2001). Using the surface currents generated from the approach above we can generate a range of peak current values and a range of internal wave widths. By comparing shifts of the internal wave packet between two SAR images we can estimate a range of phase speeds. If we assume that we know the local bathymetry and have an estimate of the density ratio across the mixed layer boundary, then we can use the two-layer model to generate the family of possible internal wave amplitudes and mixed layer depths that would give us surface current peaks, surface current widths, and phase speeds within the observed ranges.

Details on the full system can be found in Wackerman, 2009.

For a test case we have used two SAR images collected during SW06 over an internal wave packet for which there were *in situ* observations of the wave properties. The two SAR images were collected with the ERS and ENVISAT satellites about 30 minutes apart. Figure 2 shows the results of trying to reproduce the RCSM from the ERS image where the dashed red line is the actual RCSM and the solid colored lines are the model RCSM after each iteration. Note that by the third iteration (purple line) we get good agreement with the actual data. Doing this for both the ERS and ENVISAT images generates the two surface current fields shown in Figure 3. Note that they are very consistent between the two images. Finally, if we put these currents and widths, along with a phase speed estimate that comes from comparing shifts between the two images, into a two-layer model we can generate the family of waves that reproduce these observations. Figure 4 shows an example. Assuming a mixed layer depth of 15m, Figure 4 plots the peak surface current (red line), internal wave width (green line) and phase speed (blue line) that results from the two-layer model for various internal wave amplitudes (x-axis). The black arrows show the range of these values estimates from the SAR images. The shaded area represents the range of internal wave amplitudes which reproduce values for all three parameters that

are within the observed range; this is essentially a 10-11m amplitude. There were no solutions for other mixed layer depths, so in this case we estimates a unique depth (15m) and limited amplitude range (10-11m). The *in situ* CTD casts showed a mixed layer depth of approximately 15 m, and mooring temperature data indicates an internal wave amplitude of 10-15m. Thus the SAR-generated estimates were very consistent with the *in situ* observations.

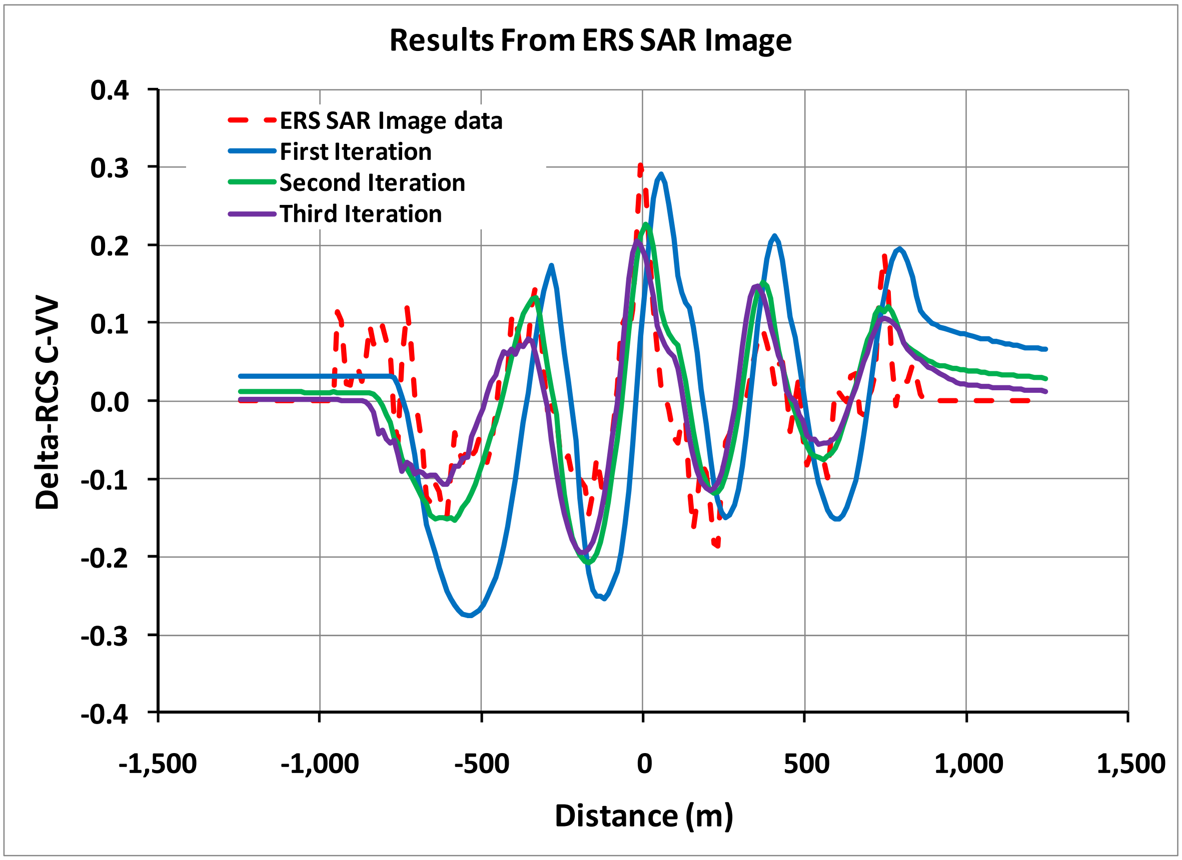

Figure 2: Model outputs for RCSM (here called Delta-RCS) for three iterations of the model versus actual RCSM values extracted from an ERS SAR image (red, dashed line). Note that by the third iteration (purple line) we have a good match to the data.

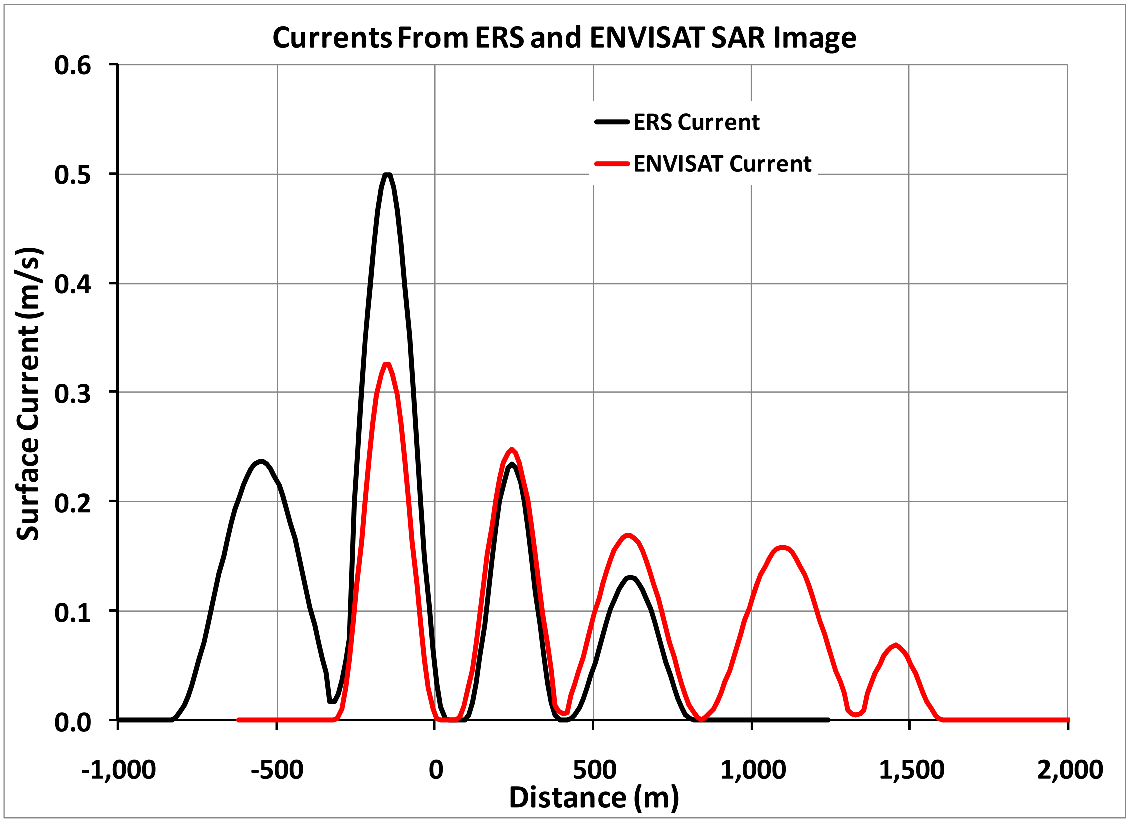

Figure 3: Surface currents resulting from an ERS SAR image and an ENVISAT SAR image over the same internal wave packet about 30 minutes apart. Note that the two current fields are very consistent in terms of peaks and widths. These are the surface currents that best reproduced the RCSM for each image.

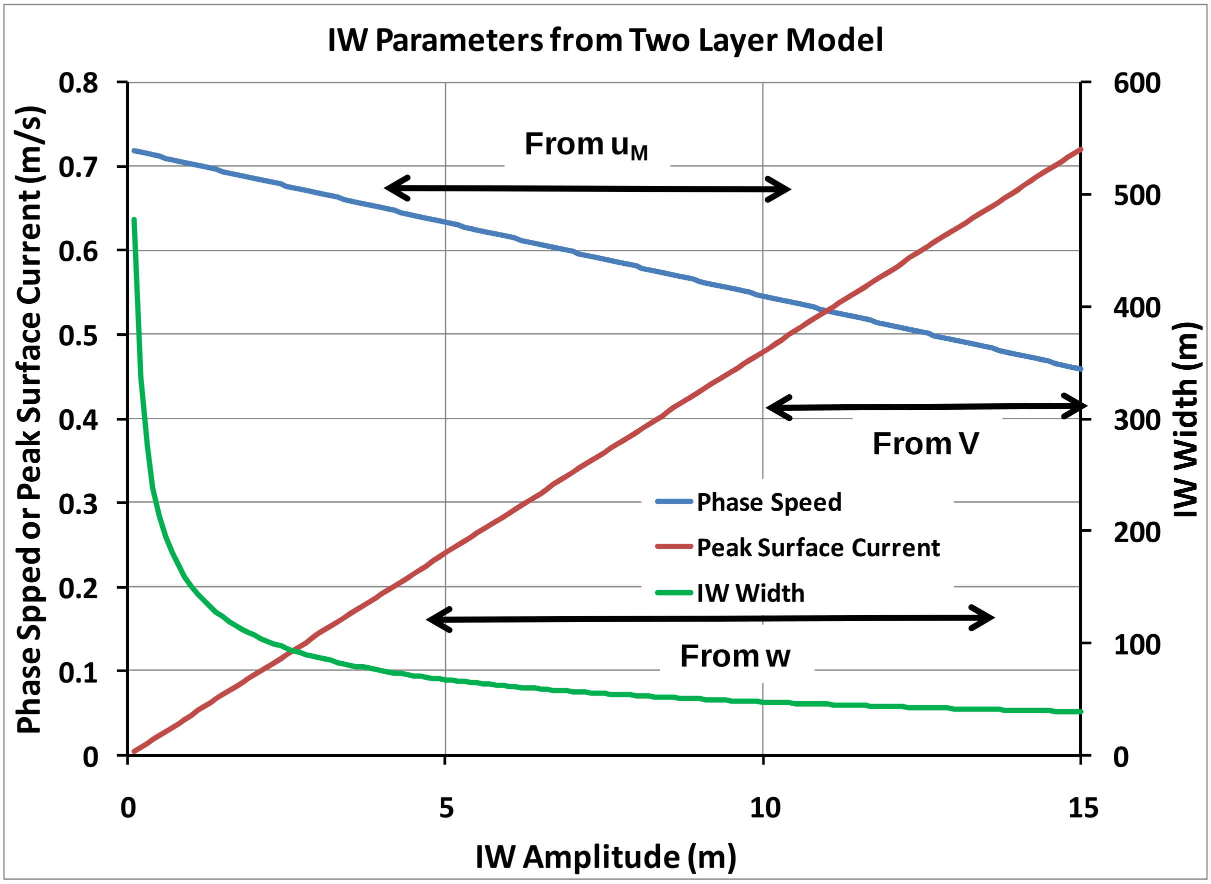

Figure 4: Results from the two-layer internal wave model to estimate surface current parameters. These results assumed a mixed layer depth of 15m; phase speed, peak current, and current width are plotted versus an assumed internal wave amplitude. The black arrows show the range of values of these parameters estimated from the SAR imagery. The shadowed region shows the internal wave amplitude that gives model results consistent with the observations; ~ 10 – 11 m.

IMPACT/APPLICATIONS

If successful, the resulting system will be one component of an operational Navy tool to allow prediction of future internal wave activity in a region so that the Navy vessels can maneuver appropriately.

TRANSITIONS

If successful, we anticipate transitioning the code for estimating internal wave parameters from SAR images to operational Navy centers for testing and exploitation.

RELATED PROJECTS

There are no ongoing related projects that are closely identified with this project.

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